STELLAR KINEMATICS IN DOUBLE-BARRED GALAXIES: THE σ-HOLLOWS

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ABSTRACT

We present SAURON integral-field stellar velocity and velocity dispersion maps for four double-barred early-type galaxies: NGC 2859, NGC 3941, NGC 4725 and NGC 5850. The presence of the inner bar does not produce major changes in the line-of-sight velocity, but it appears to have an important effect in the stellar velocity dispersion maps: we find two σ-hollows of amplitudes between 10 and 40 km s^{-1} on either side of the center, at the ends of the inner bars. We have performed numerical simulations to explain these features. Ruling out other possibilities, we conclude that the σ-hollows are an effect of the contrast between two kinematically different components: the high velocity dispersion of the bulge and the more ordered motion (low velocity dispersion) of the inner bar.

Subject headings: galaxies: kinematics and dynamics — galaxies: structure

1. INTRODUCTION

Double-barred galaxies are rather common systems in the Universe, representing $\sim$1/3 of all barred galaxies (Erwin & Sparke 2002; Laine et al. 2002). These structures are mainly seen by surface brightness profile decomposition, which requires not only a bulge and a disk but also two additional components with non-axial symmetry. The presence of inner bars does not seem to correlate with the morphological type of the host galaxy and there is also no preferred angle between the two structures (Friedli & Martinet 1993; Wozniak et al. 1995). This property suggests that both bars rotate independently, as seen in observations and consistent with numerical simulations (e.g. Corsini et al. 2003; Englmaier & Shlosman 2004; Shlosman et al. 1989; Shlosman & Heller 2002). Inner bars play an important role in the evolution of galaxies as they might transport gas to the central regions, where they may trigger the formation of stars that, in turn, lead to the appearance of new structures such as disk-like components (Martinet 1995). Theoretically, this phenomenon cannot be achieved with a single bar, since the flow of material would stop before reaching the galactic center (e.g. at the Inner Lindblad resonance). The presence of two embedded bars makes it possible and may even help to feed the central AGN (Shlosman et al. 1989, 1990).

The study of the orbital make-up of different morphological components in double-barred galaxies is one of the best ways to understand their internal structure and dynamics. Nevertheless, this is a rather complex issue to address as there are three fundamental frequencies for the regular orbits (i.e. two for the bars and one for the free oscillations; Maciejewski & Athanassoula 2007) instead of the two frequencies as in the case of a single bar. As a result, they do not have closed and periodic orbits, so Maciejewski & Sparke (2000) introduced the *loop* concept to represent the stable orbits in a double-barred potential.

A more popular approach is the use of numerical simulations to describe the structures seen in real observations, such as in the recent works by Heller et al. (2007) and Debattista & Shen (2007). In their simulations, these authors generate long-lived double bars with and without a dissipative component, respectively. However, most existing observations have relied on long-slit spectroscopy along only a few position angles (e.g. Emsellem et al. 2001), which makes the comparison with the models somewhat difficult. Better suited integral-field spectroscopy has generally not been used to observe these systems, with the notable exceptions of Moiseev (2001) and Moiseev, Valdés, & Chavushyan (2004).

Here we present SAURON integral-field spectroscopy results on the stellar kinematics of four double-barred early-type galaxies. We will focus on the detailed analysis of the stellar velocity dispersion maps, that reveal a peculiar feature, not seen before, along the extremes of the inner bar. We present the observational evidence and discuss possible interpretations using numerical simulations. A more complete account of the ionised gas, stellar population properties and supporting numerical simulations will be the subject of a forthcoming paper.

2. OBSERVATIONS, INSTRUMENTAL SETUP AND ANALYSIS

Integral-field spectroscopic data of four double-barred early-type galaxies were taken with the SAURON spectrograph, attached to the William Herschel Telescope at the Observatorio del Roque de los Muchachos (La Palma, Spain). The galaxies were selected from the catalog of Erwin (2004), so that not only the lengths of the inner bars were a good match to the SAURON field-of-view (FoV), but also allowed for enough FoV in order to sample the transition region between the two bars. We deliberately selected early-type galaxies so as to avoid the appearance of complex structures due to the presence of dust, and to make it easier to perform stellar population analysis.

We used the LR mode of SAURON providing a $33'' \times 41''$ FoV with spatial sampling of $0''\!.94 \times 0''\!.94$ per lens. The spectral range covers the domain between 4800-5380 Å. This setup produces 1431 spectra per pointing over the SAURON FoV, with a sampling of 1.1 Å pixel^{-1} and a spectral resolution of 3.74 Å (FWHM). The data reduction was performed using the XSAURON package (Bacon et al. 2001), following the same procedures outlined in Emsellem et al.

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(2004). Total integration times range between 3 to 4 hours, providing a signal-to-noise ratio of ~ 300 at the centers of the galaxies. Additionally, in order to ensure the measurement of reliable stellar kinematics, we spatially binned our final datacubes using the Voronoi 2D binning algorithm of Cappellari & Copin (2003), creating compact bins with a minimum signal-to-noise ratio (S/N) of ~ 60 per spectral resolution element. Most spectra in the central regions, however, have S/N in excess of 60, and so remain un-binned. The stellar kinematics is then extracted as described in Falcón-Barroso et al. (2006), by fitting the absorption spectrum to a linear combination of the same set of templates. For this purpose we used the penalized pixel-fitting (pPXF) method of Cappellari & Emsellem (2004) and a well selected subsample of the stellar population models from Vazdekis (1999), with evenly sampled ages and metallicities.

3. THE OBSERVED σ-HOLLOWS

Figure 1 shows the results from the analysis of the datacubes. The stellar velocity maps look very much like those of non double-barred galaxies and in three out of the four galaxies (NGC 2859, NGC 4725 and NGC 5850) we find local velocity maxima and minima along the direction of the kinematic major axes, at a few arcseconds from the galaxy centers. Moreover, the h_3 maps, not included in this letter, show a clear anticorrelation with the stellar velocities at the locations of these features, supporting the idea that these faster rotating components are kinematically decoupled inner disks (Bureau & Athanassoula 2005). Since the kinematic major axes are not aligned with the inner bars at these regions, these disks cannot be related with the bars.

However, the stellar velocity dispersion maps reveal some interesting features not seen in other morphological types of galaxies. The values measured are at a maximum at the centers of the galaxies (as seen in most E/S0 galaxies) but, instead of smooth negative velocity dispersion gradients towards the outer parts, we find two symmetrical regions where the velocity dispersion values drop significantly compared to their surroundings. These σ-hollows are located exactly along the major axes of the inner bars and they extend out to the edges, as we checked with several tests. The amplitude of the hollows varies between 10 and 40 km s^{-1}. Interestingly, neither the H$_\beta$ or [OIII] emission-line maps (not presented here) show any distinct features at the same locations of the inner bars. The stellar velocity dispersion map for NGC 5850 was previously shown by Moiseev, Valdés, & Chavushyan (2004), but no hollows are seen in there; we believe this is because the smaller FoV of the MPFS instrument used in those obervations.

4. DISCUSSION: THE ORIGIN OF THE σ-HOLLOWS

Since the σ-hollows of the four galaxies are observed exactly at the ends of the inner bars, it seems that they are related to the inner bar itself and not to any other structural or kinematical component. The aim of this section is to investigate the origin of the σ-hollows, so in the following we discuss some possible explanations for these observations.

4.1. *The presence of an inner disk*

Stellar inner disks could, in principle, explain a decrease in velocity dispersion in the central regions of galaxies, as happens with the σ-drops seen in Emsellem et al. 2001. However, the observed alignment of the σ-hollows with the major axis of the inner bar cannot be accounted for with the presence of an inner disk whose major axis is usually well aligned with the main photometric major axis of the galaxy. Moreover, the decrease in σ in our galaxies does not occur at the same locations as the σ-drops seen by Emsellem et al. (2001); in fact we find that the velocity dispersion reaches a maximum value at the center. The possibility of a gaseous inner disk is discarded because the effect we see in our data is purely stellar.

4.2. *A young stellar population component*

A young stellar component that has acquired the kinematics of the cold gas it was formed from could also explain the decreases in the velocity dispersion values. This young population might not necessarily be associated with a different structural component (e.g. a nuclear star forming ring). We tested this hypothesis by performing a preliminary stellar population analysis of the different structures to investigate the presence of young stars (an extensive stellar population analysis will be published elsewhere). However, we do not find any evidence of the presence of a particularly young stellar population at the σ-hollows locations.

4.3. *A matter of contrast*

We now focus on the immediate surroundings of the inner bar. In the central parts of these galaxies we have the combination of a component with typically high velocity dispersion (i.e. a bulge) and the inner bar with its ordered motion and thus a low σ. We propose that the presence of the σ-hollows is due to the contrast between the velocity dispersion of these two components. Since the velocity dispersion profile and the luminosity profile of the bulge decreases outwards, we can only see this effect in the outer parts of the inner bar, where the bulge is not totally dominating the flux. Therefore the amplitude of the hollows will depend on the relative contribution of the bulge to the total luminosity at the extremes of the bar and on the difference of velocity dispersions between the bulge and the inner bar. Irrespective of the relative luminosity of the two components at the edges of the inner bar, if there were no differences between the velocity dispersions we would not be able to find any σ-hollows. Assuming that there is a significant difference in the σ values at these points, a very extended bulge may have the inner bar embedded in it, so we would expect very deep σ-hollows in this case. On the contrary, if the bulge were less extended these σ-hollows would not show up.

To test this idea we used the code FTM 4.4 (updated version) from Heller & Shlosman (1994) to perform N-body self-consistent three-dimensional numerical simulations starting with a (classical-like) bulge and an exponential disk. First, we relax the bulge, in order to have a "quiescent" start, and then we introduce an exponential self-graviting rotating disk. The bulge proceeds to evolve almost steadily, contrary to the disk, which develops a bar instability. Here, we use simulations with a

single bar to mimic the main components in the region of interest: the central kiloparsec. This simple approximation is enough to reproduce the σ-hollows: they appear at the ends of the bar for the cases in which the contrast is sufficient. These σ-hollows last as long as the bar stays with a low σ. Stellar bars in general could be heated-up by the buckling instability, which is milder in the presence of gas (Berentzen et al. 1998, 2007) and in weak bars (Martinez-Valpuesta & Shlosman 2004). Since the four observed inner bars presented here are not very strong (Erwin 2004) and there is some gas in these regions, most likely they will not buckle. Therefore, we expect the σ-hollows to be long-lived structures.

In Figure 2 we illustrate two of our models: one case of a bulge large enough to match the length of the bar, where we are able to reproduce the σ-hollows, and one case with a smaller, less extended bulge where the velocity dispersion profile is almost unchanged. The simulations shown here use a galaxy inclination of $30°$ (as a representative case of our observations) and a position angle of $20°$ for the bar. However, we repeated the tests with different observational conditions, getting similar results in all cases. Note however that recent numerical simulations of double-barred systems by Shen & Debattista (2007) do not show any evidence of the presence of the σ-hollows in their velocity dispersion maps. A possible explanation for this absence is the fact that in those simulations there is not sufficient velocity dispersion difference between the resulting structural components.

5. CONCLUSIONS

We have presented 2D kinematical maps of double-barred early-type galaxies covering the whole nuclear region. We have found σ-hollows appearing at the ends of the inner bar for our four objects. The main result presented in this paper is that these hollows are signatures of inner bars, which indicates that it they must have significantly lower velocity dispersions than the surrounding bulges. This means that inner bars are cold systems, and

are not related to triaxial bulges (Kormendy & Kennicutt 2004). Moreover, the observations presented here put constraints on the degree of rotational over pressure support for these structural components. Finally, since the σ-hollows are not due to other structural or kinematical components (e.g. inner disks), they may be used to identify inner bars from a purely stellar kinematic analysis.

It is likely that previous numerical simulations were unable to predict the observed σ-hollows because they did not include a sufficiently dynamically hot component (i.e. classical bulge). However, we have been able to reproduce this feature with simulations including a hot bulge, a single small bar and a disk. The σ-hollows can be seen due to a contrast between the high velocity dispersion of the bulge and the low velocity dispersion of the bar. The amplitude of the hollows depends on the relative contributions to the total flux and the relative sizes of the bulge and the inner bar. While young stellar populations can help to lower the stellar velocity dispersion, no clear signatures of them are found in our sample. Based on the pieces of evidence presented in this paper, we think that the σ-hollows are simply a matter of contrast.

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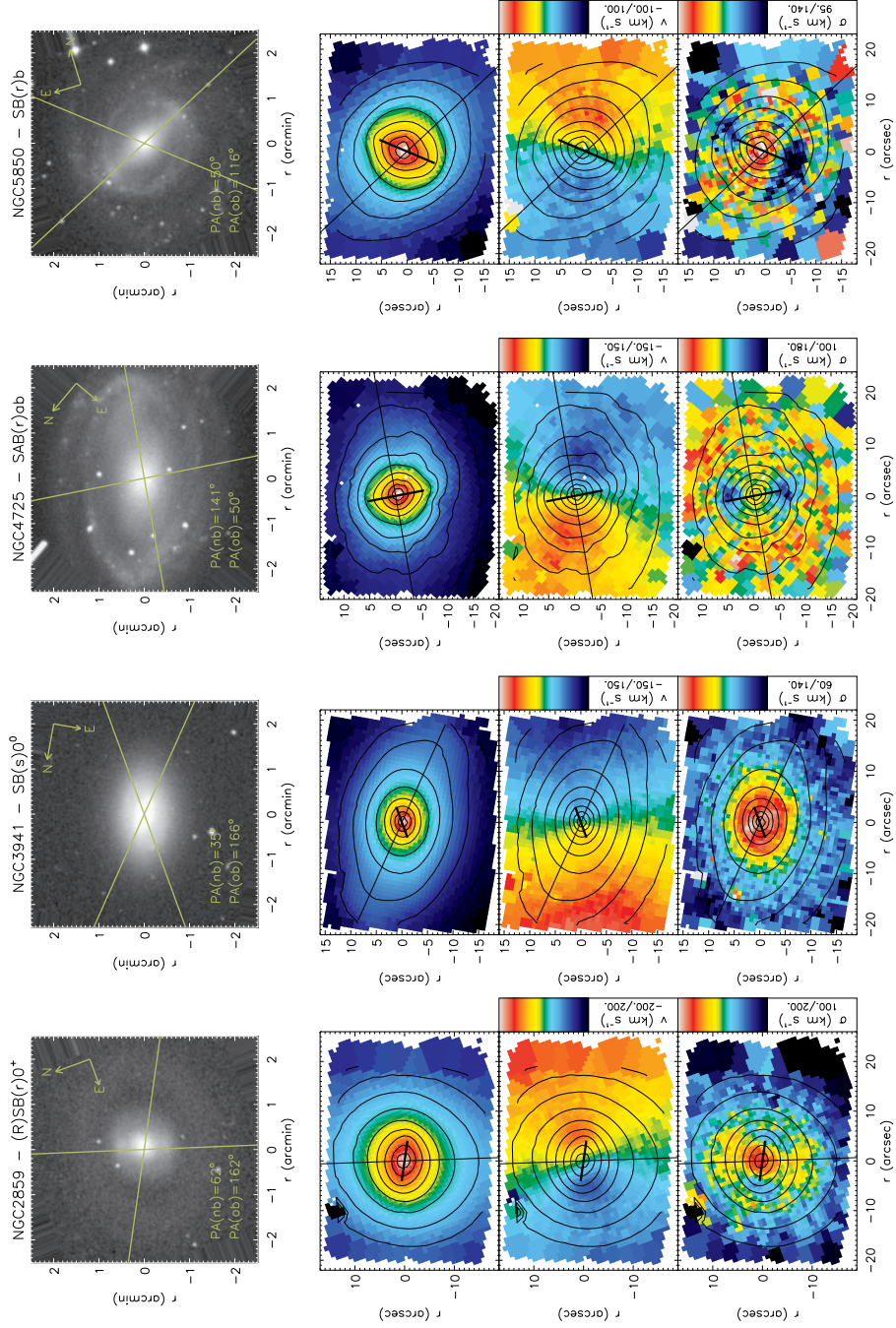York, D. G., et al. 2000, AJ, 120, 1579

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FIG. 1.— Maps of the stellar distribution and kinematics of the 4 double-barred galaxies in our sample: an optical image from the Sloan Digital Sky Survey (York et al. 2000) together with our intensity maps and the stellar velocity and stellar velocity dispersion maps are shown for each galaxy. We have overplotted the position angle of the inner bar (thick line), the outer bar (thin line) and the contours of the reconstructed total intensity from our own datacubes. Note the presence of the σ-hollows at the edges of the four inner bars; these hollows are clearly seen in the velocity dispersion maps of NGC 2859, NGC 4725 and NGC 5850 whereas they are less evident (that is, they have lower amplitudes and their presence is evident from cuts along the inner bar) for the case of NGC 3941.
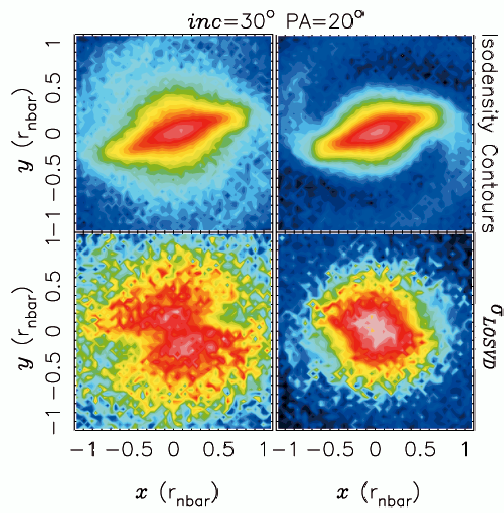
FIG. 2.— Numerical simulations including a bulge, a bar and a disk. Top panels: iso-density contours; lower panels: LOSVD. On the left is the case for a bulge big enough to match the size of the bar: the corresponding LOSVD map shows clearly the σ-hollows. On the right is the case of a very small bulge, whose luminosity drops quickly with radius such that its contribution is not relevant at the ends of the bar. The σ-hollows in this case become difficult to detect.